SPECIFICATIONS OF THE DISTRIBUTED TIMING SYSTEM FOR THE CLIC MAIN LINAC

A. Gerbershagen, A. Andersson, D. Schulte, CERN, Geneva, Switzerland
P. N. Burrows, JAI, University of Oxford, Oxford, UK
F. Ömer Ilday, Bilkent University, Ankara, Turkey

Abstract

The longitudinal phase stability of the CLIC main and drive beams is a crucial element of the CLIC design. In order to measure and control the phase a distributed phase monitoring system has been proposed. The system measures the beam phase every 900 m. The relative phase between the measurement points is synchronized with an external reference system via a chain of reference lines. This paper presents the simulations of error propagation in the proposed distributed monitoring system and the impact on the drive and main beam phase errors and the luminosity. Based on the results the error tolerances for the proposed system are detailed.

INTRODUCTION

The Compact Linear Collider (CLIC) is a proposed 3 TeV center-of-mass energy e^+e^- collider. It is designed to extract the RF energy from high-current low-energy drive beams and use this energy for acceleration of the low-current high-energy main beams that are brought into collision.

Since the main beam acceleration is performed by the RF power extracted from the drive beam, the stability of the relative phasing of the drive and main beams is crucial for the preservation of CLIC's luminosity. A relative phase error of 0.2° @ 12 GHz between the drive and the main beam will cause a luminosity loss of 1% if the error is coherent between the 24 decelerator segments. The same luminosity loss can be caused by an incoherent error of 0.8°. [1]

Additionally to these requirements on the relative drive beam - main beam phase, the phase tolerance between the two main beams at the interaction point (IP) has been set to 0.6° @ 12 GHz [2]. Hence, in order to align the main beam phase a global phase reference over 50 km is needed.

The stated tolerance requirements have to be met on the timescale of ≈50 ns, since this is the beam loading time of the main beam accelerating structures and errors on the shorter time scale will be (at least partially) filtered out by the structures.

PROPOSED DISTRIBUTED TIMING SYSTEMS

The distributed timing system is required to establish the correct beam phase at each turn-around of the linac. This allows to measure and correct the main and drive beam phases along the main linac. There are two approaches for the design of such a system.

The first approach (A) is to use the outgoing main beams to transmit the phase information to a number of local oscillators (Fig. 1, top). These can maintain the phase accurately enough until the main beam returns on the way to the interaction point. This system requires accurate phasing between the outgoing main beams at the first booster linac near the interaction point (Fig. 2).

In the other approach (B) the master clock near the interaction point (IP) would define the nominal phase and distribute it as a signal cascade from one 900 m long decelerator segment to another (Fig. 1, bottom). This system would establish the relative phase of the local timing clocks by an optical connection independently of the beams.

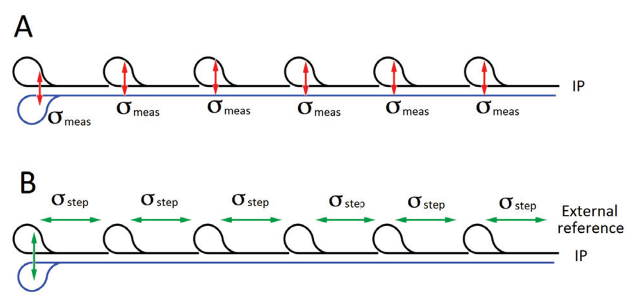

Figure 1: Phase signal propagation for the reference based on the main beam (A) and chained distribution of master clock signal (B).

Approach A has the advantage of having a relatively small error between the main and the drive beams, since the phase measurement at each drive beam decelerator is performed locally and hence no additional error is introduced during the distribution process (see Fig. 3, left). Approach B allows the correction of the main beam at its final turnaround, giving the possibility to reduce the jitter between the e^+ and e^- main beams (Fig. 3, right). However, if the drive beam correction signal is transported from the master clock via the distribution system, the noise introduced by this system would reduce the effectiveness of the phase correction. In the final CLIC design these approaches could be potentially combined.

The proposed timing distribution system is based on state of the art technology for signal distribution via optical fibers tested at XFEL (DESY, Hamburg) [3], [4]. This system is proven to provide <10 fs stability over the distance of several kilometers.

The following analysis determines the specifications of the

ISBN 978-3-95450-122-9

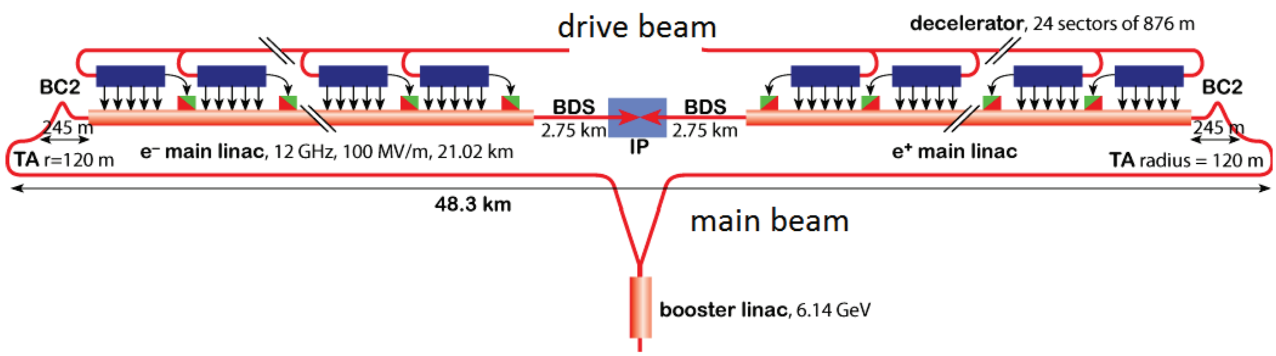

Figure 2: CLIC layout at 3 TeV.

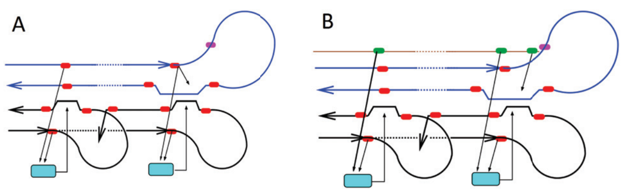

Figure 3: Phase correction system based on the main beam phase measurement (A) and on the external master clock (B) [2].

second approach (distributed timing system) and sets the requirements for the tolerances of this system.

ANALYSIS OF SPECIFICATIONS FOR THE DISTRIBUTED TIMING SYSTEM

Principle of time distribution and phase correction

As shown in Fig. 3 B, the signal from the master clock is used as the synchronization signal for the local oscillators. The master clock itself has a particular noise spectrum [5]. The impact of the noise on the local oscillators can be reduced by integrating the signal over the time intervals longer than the beam propagation time through the machine (≈ 0.2 ms).

The correction of the main beam is performed at the final turnaround with help of a kicker chicane, which can change the path length of the main beam bunches and hence their longitudinal position. The drive beam phase is also corrected via a chicane to the nominal value defined by the master clock at the turnarounds at each of the 24 decelerator modules.

The phase measurements on the main and drive beam after the chicanes ensure that the provided correction had the right value. If it is not the case, this could mean that the path length of the beams in the chicane is not as predicted, the chicane has the wrong R_{56} value or that the waveguide length has changed (e.g. due to temperature variation). To correct for these changes, a pulse-to-pulse feedback system can be introduced. Provided the changes are slow enough, the measured value of the correction error can be used to adjust the relative definitions of the monitors' nominal phase. The new definitions will ensure that the correction for the next pulse will set the drive beam bunches closer to their nominal position relatively to the main beam bunches. Hence, high stability of the local oscillator clocks must be ensured on a timescale of 20 ms, which is the pulse-to-pulse interval of CLIC.

In order to calculate the phase tolerance for signal transfer between the two subsequent decelerators, σ_{step}, (Fig. 1, B), one must calculate the impact of this error on the total phase error. We will assume a random walk of the phase error, which starts from the master clock at the IP and propagates along the machine step by step from one drive beam decelerator segment to another.

e^+ and e^- main beams phase tolerance

For the incoming main beams the relative phase tolerance at the IP is $0.6°$ @ 12 GHz $\triangleq$ 42 μm $\triangleq$ 140 fs [2] which corresponds to 1% of luminosity loss. Hence, one must assure that the total phase error introduced by the distributed timing system σ_{dts} is below $(140\text{ fs})/\sqrt{2}$ for each of the main beams.

Additionally to the 24 decelerator modules, each about 900 m long, we must consider that the beam delivery system of each main beam is about 2.75 km long [8]. To simplify the calculation it will be assumed that the distributed timing system for the main beam is 27, instead of 24, sectors long, hence about 2.7 km longer. One can consider the errors at each of the segments as linearly independent. Hence, the tolerance for the phase error introduced in each segment is given by

$$\sigma_{step,mm,1\%} = \frac{140\ fs}{\sqrt{27} \times \sqrt{2}} = 19.05\ fs \triangleq 5.72\ \mu m. \quad (1)$$

The stated correction system error would cause a luminosity loss of 1%. However, in reality the largest part of the tolerance budget will be reserved for the beam itself and not for the reference jitter. Hence, the calculation only determines the upper limit for the distribution error but not

ISBN 978-3-95450-122-9

the effective system requirement, which will depend on the expected beam phase jitter. Defining the distribution system requirement to causing max. 0.1% luminosity loss, one obtains $\sigma_{step} = 5.72\ \mu m/\sqrt{10} = 1.81\ \mu m$
An advantage of the distributed timing system is that it allows to loosen the phase tolerances on the outgoing main beam by a factor of 7, since the phase correction at the final turnaround of the main beam can reduce the phase error [1], [7]. Also, the phase correction can compensate for the change in the main beam path length, given the path length change is slow enough ($\ll 20\ ms$ pulse interval).

Main beam - drive beam phase tolerance

The error σ_{step} causing 1% luminosity loss can be calculated from the main beam - drive beam relative phase error tolerance. The total error σ_{tot} introduced by the phase correction system at each decelerator must be below 0.8° @ 12 GHz for uncorrelated errors.

We assume a random walk of the distribution error segment by segment. The impact of each error is given by $\sum_{j=1}^{i} \sigma_{step}$ with i being the number of the segment counted from the IP. The total error introduced by the distributed timing system σ_{dts} is given by the sum of the errors in all segments. One should also consider that the main beam bunches are positioned at 30° of the RF wave in the four segments nearest to the IP and at 8° in other 20 segments. Hence σ_{dts} is given by

$$\sigma_{dts}^2 = \sum_{i=1}^{4}\left(\sum_{j=1}^{i}(\sigma_{step} \times \sin 30^\circ)\right)^2 + \sum_{i=5}^{24}\left(\sum_{j=1}^{4}(\sigma_{step} \times \sin 30^\circ) + \sum_{j=5}^{i}(\sigma_{step} \times \sin 8^\circ)\right)^2$$

Normalising σ_{dts}^2 by the RMS value of the stated sine functions and calculating the sums, one obtains

$$\sigma_{step,md,1\%} = 0.059^\circ \triangleq 4.12\ \mu m \quad (2)$$

This value is of the same order of magnitude as the tolerance given by the main beam - main beam phase error consideration ($\sigma_{step,mm,1\%} = 5.72\ \mu m$) calculated in the previous sub-section. Defining as above the maximal 0.1% luminosity loss as a specification of the distribution system, the requirement for the reference stability will be $4.12 \mu m/\sqrt{10} = 1.30\ \mu m$.

The 1% luminosity loss from the reference jitter has been calculated independently for main beam - main beam and main beam - drive beam phase error tolerances. In reality the same reference jitter σ_{step} would cause a luminosity loss via both channels,

$$\Delta\mathcal{L}_{total} = \Delta\mathcal{L}_{md} + \Delta\mathcal{L}_{mm}$$
$$= 1\% \times \left(\left(\frac{\sigma_{step}}{\sigma_{step,md,1\%}}\right)^2 + \left(\frac{\sigma_{step}}{\sigma_{step,mm,1\%}}\right)^2\right)^2$$

Solving this equation for $\Delta\mathcal{L}_{total} = 1\%$ yields $\sigma_{step} = 3.34\ \mu m$. However, $\Delta\mathcal{L}_{total} = 0.1\%$ defines the specification of $\sigma_{step} = 1.06\ \mu m$ average error introduced by the distributed timing system at each decelerator segment.

CONCLUSIONS AND OUTLOOK

The phase jitter of the distributed timing system at each decelerator segment is calculated to be 3.34 μm for 1% luminosity loss from both the main to main and main to drive beam tolerances.This value is met by demonstrated performances [3], [4], which proves the feasibility of the distributed timing system. However, ideally the specification would be tighter - 0.1% luminosity loss, which requires a distribution system stability of 1.06 μm per segment. Hence, it has to be investigated whether the noise can be significantly reduced.

The demonstrated performance of the signal distribution includes the transformation of the optical signal into electrical and vice versa. One solution could be chaining the distribution by splitting the optical signal at each decelerator, using one part of the signal as a reference and amplifying the other part and sending it to the next decelerator. This would help to avoid transformation noise and might allow to reach the specified target. A dedicated approach would be needed to prove this concept experimentally.

It will be also necessary to demonstrate the reliability of the signal distribution technology to operate unattended in the tunnel.

REFERENCES

[1] D. Schulte et al., "Status of the CLIC Phase and Amplitude Stabilisation Concept", Proceedings of Linear Accelerator Conference LINAC2010, Tsukuba, Japan MOP024

[2] D. Schulte, First CLIC Phase Stability Meeting, November 24, 2011, `http://indico.cern.ch/conferenceDisplay.py?confId=164428`.

[3] F. Ömer Ilday, "Long-distance optical stabilization with femtosecond resolution", CLIC09 Workshop

[4] M. Felber, "Achievements and challenges during the first implementation phase of an engineered version in the accelerator", CLIC09 Workshop

[5] CLIC Conceptual Design Report, chapter 5.14, "Fine time generation and distribution"

[6] A. Andersson, "Phase reference system", CLIC collaboration meeting, May 10, 2012

[7] F. Stulle, "Beam phase and energy tolerances in the CLIC RTML", CLIC - Note - 874

[8] CLIC Parameter Table, `http://clic-meeting.web.cern.ch/clic-meeting/clictable2010.html`

ISBN 978-3-95450-122-9